Numerical Pile Driving Analysis for Non-Uniform Piles

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ABSTRACT: This paper focuses on the effect of pile shape in the penetration of pile and magnitude of stress in pile body. For this purpose, concrete tapered piles of the same volume and length is considered. All piles have conic shape with different slopes along the shaft. In all analyses, the hammer impact is modeled using a single function which obtains from current literatures. The subsoil is assumed as normally consolidated clay. The soil is assumed to be saturated and undrained. Linear elastic behavior is assumed for the pile whereas the Mohr-Coloumb failure criterion is considered for clay. Interface elements are used to allow the slip between the pile and the soil. To ensure the correctness of the constructed numerical pile driving models, the results obtained from this proposed model is compared with numerical data obtained from an available sophisticated analysis. Parametric studies have been carried out to determine the influence of contributing factors such as tapered angle and soil stratification on pile driving phenomenon. The effect of taper angle on permanent pile penetration and driving stresses will be presented.

KEYWORDS: non-uniform piles; pile driving; finite element method; set; driving stress; undrained condition; normally consolidated clay

1. INTRODUCTION

The bearing capacity of deep foundation is a major task in foundation design. To this aim, an appropriate modification of the pile geometry may be chosen. Recent research work carried out on tapered piles subjected to various loading has shown that that such piles may be superior to prismatic piles of the same volume and length (Ghazavi, 2000; Ghazavi, 2003; Ghazavi and Ahmadi Bidgoli, 2002; Ghazavi, et al., Hashemolhosseini, 2003; Ghazavi and Etaati, 2001; Ghazavi et al., 1996; Ghazavi et al., 1997a; Ghazavi et al., 1997b).

2. NUMERICAL ANALYSIS

Finite element method is a powerful technique to examine various options in foundation design before the construction stage is started. For this purpose, the procedure uses an axisymmetric discreitization and takes into account the nonlinear behavior of the soil by Mohr-Coloumb model. Linear elastic elements are assumed for the concrete pile behavior. Interface elements are used to allow the slip between the pile and the soil. Special viscous transmitting boundaries are added to the soil in the far field to absorb the radiating waves resulting from the blow of the hammer. The impact of the hammer on the pile is represented by a periodic forcing function applied at the top of the pile, simulating a single blow. A prebored hole is considered for the single blow. A transient dynamic analysis, using time steps with the average-acceleration algorithm is performed. To ensure the correctness of the constructed numerical pile driving model, the results will be compared with those reported by Mabsout et al. (1995).

The current study is limited to round and conic concrete driven piles with same volume and length.

2.1 SOIL CONSTITUTIVE MODEL

In the study reported herein, the well-known Mohr-Coloumb failure criterion is used for modeling of the clay and sand behavior. When implementing the Mohr-Coloumb model for general stress states, a special treatment is required for the intersection of two yield surface. Some investigators (for example Smith and Griffith, 1982) use a smooth transient from one yield surface to another, i.e. the rounding of the corners, however the exact form of the full Mohr-Coloumb model uses a sharp transition from one yield surface to another. The Mohr-Coloumb model is used in this paper is the second one. The readers are referred to Koiter (1960) and Langen and Vermeer (1990) for details on this model.

2.2 FINITE ELEMENT MODEL

An outline of the finite element formulation is presented in this section (Zienkiewicz and Taylor, 1991). The basic equation of time-dependent movement of a volume under the influence of a dynamic load is:

$$\underset{\sim}{M}\,\ddot{\underset{\sim}{U}}+\underset{\sim}{C}\,\dot{\underset{\sim}{U}}+\underset{\sim}{K}\,\underset{\sim}{U}=\underset{\sim}{F} \tag{1}$$

where M is the mass matrix, U is the displacement vector, C is the damping matrix, K is the stiffness matrix and F is the load vector. By using the Newmark scheme method, Eq. (1) may be modified to:

$$(c_0\underset{\sim}{M}+c_1\underset{\sim}{C}+\underset{\sim}{K})\Delta\underset{\sim}{U}^{t+\Delta t}=\underset{\sim}{F}_{ext}^{t+\Delta t}+\underset{\sim}{M}(c_2\dot{\underset{\sim}{U}}^{t}+c_3\ddot{\underset{\sim}{U}}^{t})+\underset{\sim}{C}(c_4\dot{\underset{\sim}{U}}^{t}+c_5\ddot{\underset{\sim}{U}}^{t})-\underset{\sim}{F}_{\text{int}}^{t} \tag{2}$$

where coefficients c_0 to c_5 denote the time steps and α and β are the integration parameters. In many cases, the standard coefficient of $\alpha = 0.25$ and $\beta = 0.5$ may be used.

The finite element discreitization is based on the axisymmetric 15 node triangular element. Each node has 2 degrees-of-freedom for displacement and one for excess (pore) pressure. For undrained conditions, the element is simple to use and performs satisfactory. Another important element type in this study is interface element. The corresponding interface element for 15 node triangular elements is defined on 5 pairs of nodes. In the finite element formulation coordinates of each node pair, are identical. This means that these elements have zero thickness. But they have a 'VIRTUAL THICKNESS' which is an imaginary dimension used to obtain the material property of the interface. So by use of these elements, as penetration is detected, sliding friction of the Coloumb type is modeled. For more details on interaction elements reader should refer to Langen and Vermeer (1991).

Special absorbing boundaries are introduced for the soil far field to transmit the incident wave resulting from the driving process and, therefore prevent their reflection and thus avoiding the spurious response.

A conic and cylindrical, solid, concrete pile, driven in normally consolidated clay is considered. While the case chosen is a practical hammer-pile-soil system, it is not within the scope of this work to check the results against actual or experimental case in the field. The main purpose of the current study is to simulate the pile-driving process and determine the effect of taper angle of the pile on the pile penetration and magnitude of driving stresses.

A driving analysis for a pile already in place at a certain depth is assumed, as shown in Fig. 1. A single blow is simulated using a transient force function applied as a uniform pressure on the top of the pile. The force-time variation is illustrated in Fig. 2, as used by Goble et al. (1980).

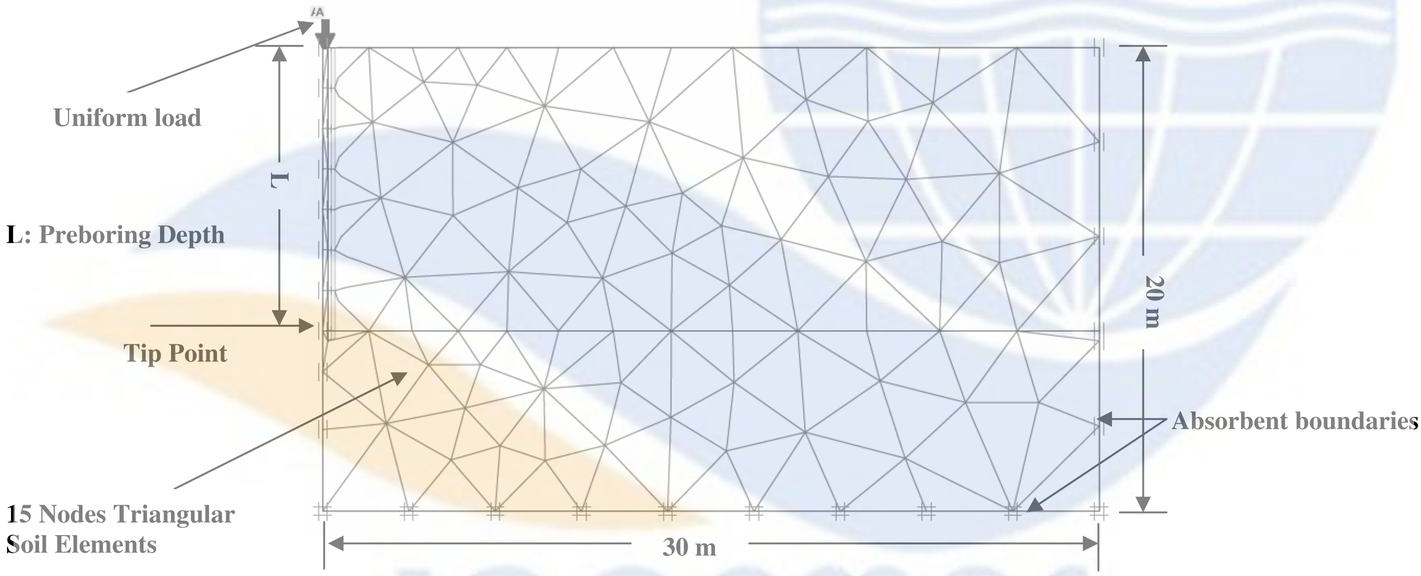

FIG. 1. Axisymmetric Finite Element Discretization of Pile-Soil System

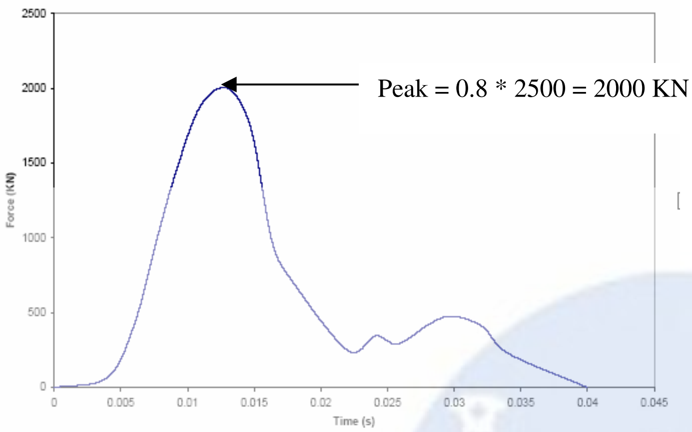

FIG. 2. Force Time Function Simulating a Hammer Blow

The geometries of all piles are shown in Fig. 3. The properties of the pile material are given in Table 1. The clay is modeled using the simple Mohr-Coloumb criterion. An interface reduction factor is used to simulate the reduced friction along the pile shaft. Table 2 shows the properties of the clayey soil. In particular, this soil refers to the laboratory-prepared kaolin clay used in the triaxial-test simulation of bounding surface model with Kaliakin and Dafalias (1989).

The soil skin friction and end bearing are chosen according to Tomlinson (1957). The adhesion factor R_{int} depends on the soil strength and the method of pile installation. This value is used based on the recommendation made by Mabsout et al. (1995).

3. VERIFICATION

To ensure the correctness of propose numerical procedure of pile driving, the results are compared with the numerical results reported by Mabsout et al. (1995) for a cylindrical pile (Fig. 4). This comparison is reasonable.

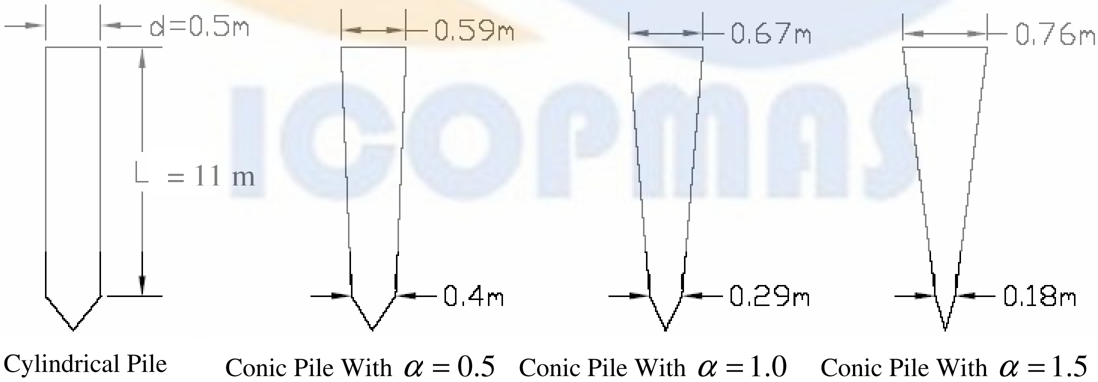

FIG 3. Geometries of Prismatic and Tapered Piles

TABLE 2. Clayey Soil Properties (Z in meters)

TABLE 1. Pile Material Properties

Parameter	Magnitude
Unit Weight (γ)	23.54 KN/m^3
Young's modulus (E_{ref})	2.48e+7 KN/m^2
Poisson's Ratio (ν)	0.2
Interface Strength-Reduction (R_{int})	1.0 (rigid)

Parameter	Magnitude
Dry Weight (γ_{dry})	16 KN/m^3
Wet Weight (γ_{wet})	20 KN/m^3
Young's Modulus (E_{ref})	1000*Z KN/m^2
Poisson's Ratio (ν)	0.3
Cohesion (C)	2.87*Z KN/m^2
Friction Angle (φ)	2 degree
Dilatancy Angle (ψ)	0.0
Interface Strength-Reduction (R_{int})	0.67

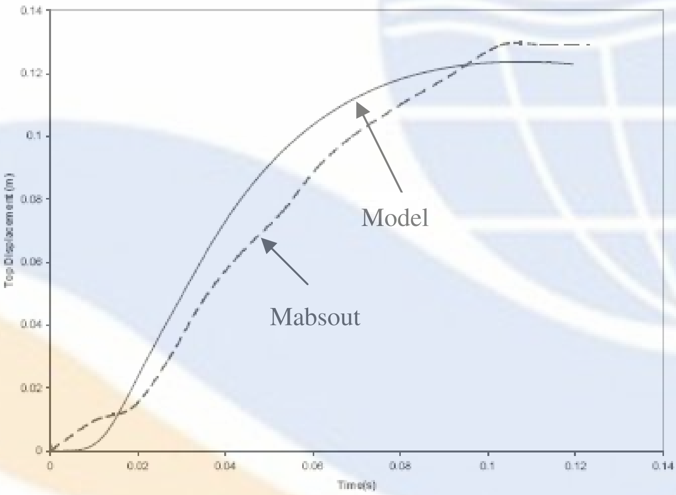

FIG. 4. Pile Head Displacement Predicted by Two Methods

4. PARAMETRIC STUDIES

The results of the pile-driving system for a single blow are presented in this section.

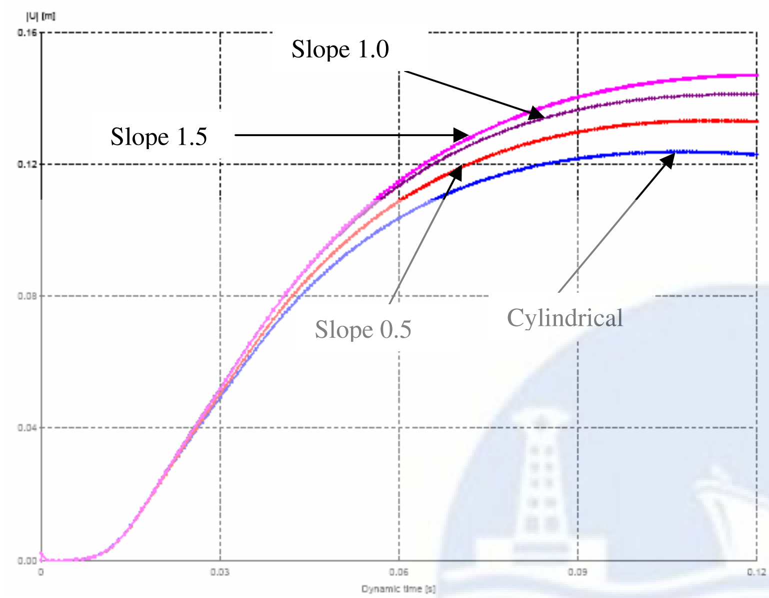

FIG. 5. Comparison of Results for Tip Displacement of Piles

4.1 EFFECT OF TAPER ANGLE

The effect of taper angle of pile on the pile penetration due to a single blow is investigated in this section. The case of normally consolidated clay given in Table 2 is analyzed for the taper angles of 0.5, 1, and 1.5 degree and also for 0 degree (cylindrical pile). As seen in Fig. 5, the pile penetration increases with increasing the taper angle. This is reasonable, since the soil is more easily punched by conical shape of the pile.

4.2. EFFECT OF PREBORING DEPTH

In this section the effect of preboring depth on the pile set is investigated. The pile taper angle is considered 1^{o}. The tip is located at depths 8, 10, and 12 m. Fig .6 shows the results. As seen, the pile penetration increases with increasing the embedded depth. This is attributed to greater soil strength with depth, leading to a larger pile-soil contact providing higher skin friction.

4.3. EFFECT OF SOIL STRENGTH

A tapered pile with 1^{o} taper angle at a penetration depth of 12 meter is assumed. The values of soil cohesion are assumed to be 2.87Z to 8Z, where Z denotes the depth in meter. Fig. 7 shows that the penetration depth is reduced by increasing the strength of the soil, as expected. Also the blow effect vanishes for greater soil resistance more quickly. The final pile penetration embedded in more resistant soil is only about 8 mm.

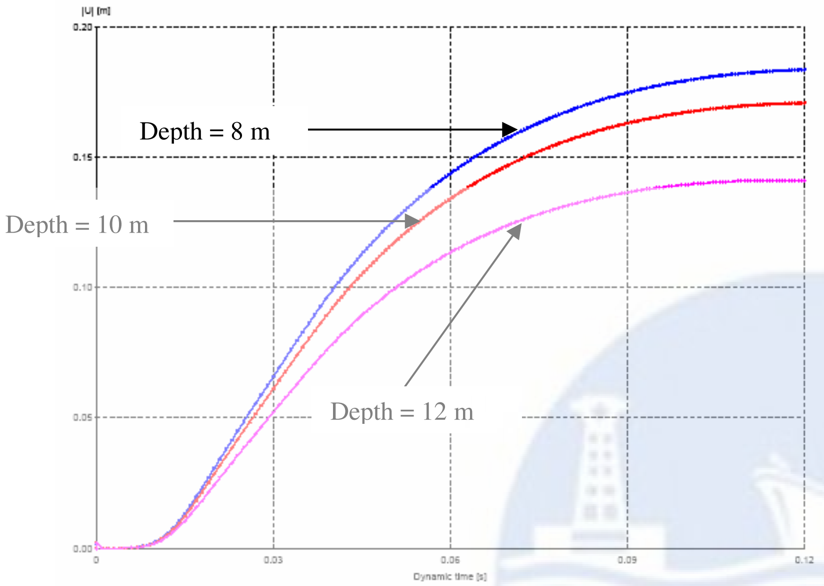

FIG. 6. Comparison of Result for Pile Penetration at Various Embedded Depths

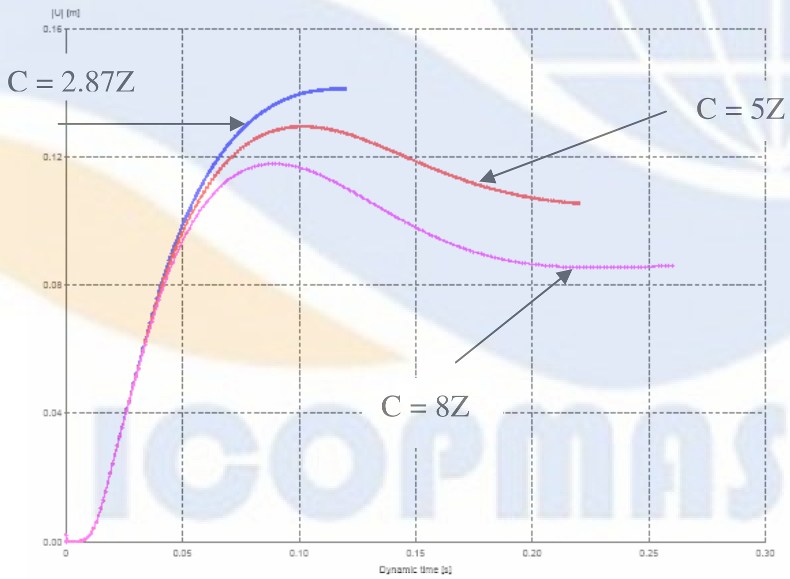

FIG. 7. Effect of Soil Strength on Pile Penetration

5. CONCLUSION

A finite element model for the analysis for driving concrete prismatic and tapered concrete piles embedded in undrained, saturated, and normally consolidated clay has been performed. The model has been verified using available data reported by Mabsout and Tassoulas (1994) and Mabsout et al. (1995). The results of analysis show that conic pile penetration under a single blow is more than cylindrical pile of the same volume and length. The penetration also increases with increasing the taper angle. Moreover, at greater pile embedment, the pile penetration decreases. More theoretical analyses together with laboratory and field tests are required o generalize the findings in this paper.

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